

First Results from DIONISOS on Deuterium Retention in Molybdenum



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PFC meeting

UCSD

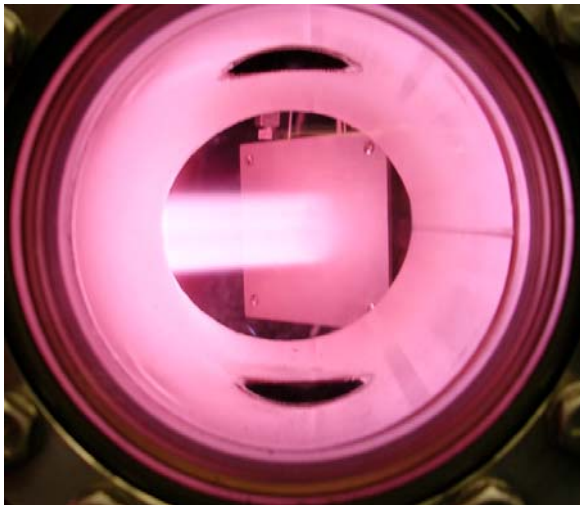
San Diego, March 2006

DIONISOS

Dynamics of IONic Implantation & Sputtering On Surfaces



**Steady-state plasma
exposure for
Fusion Materials**



+

**In-situ, real-time
Ion beam diagnostics
of Erosion, deposition
& hydrogen retention**

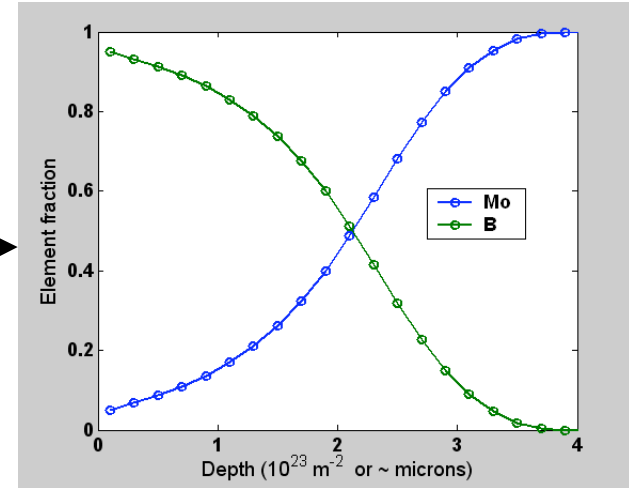
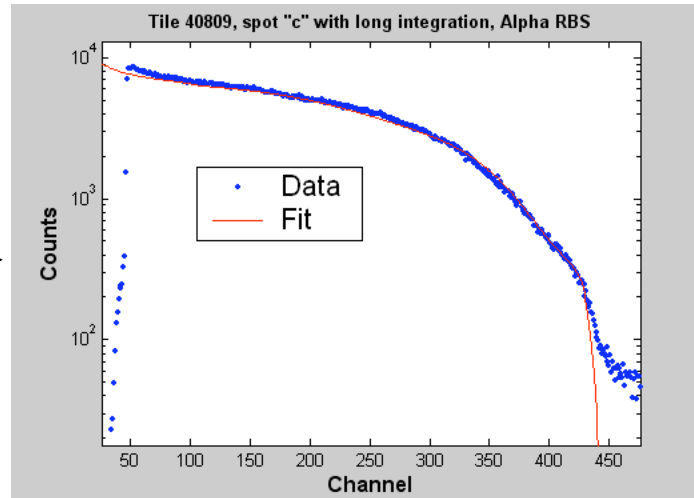


What DIONISOS brings to PFC research



- 1) Steady-state exposure of PFC materials to fusion-like plasmas &
 - 2) In-situ ion beam surface analysis WITHOUT removal of the sample
but that is only the overall description
- Because the DIONISOS plasma has a n_e , T_e profile in radius, and the ion beam analysis is spatially resolved one ***simultaneously*** obtains
 - Flux, fluence, ion energy & temperature dependence on ONE sample.
 - Radial net erosion/deposition profiles caused by sputtering and transport.
 - H/D retention, migration & release in the materials and deposited films.
 - **Plus, dynamic surface effects in the presence of a plasma.**
 - **Goal:** A laboratory facility that can provide both fundamental PSI data & Replicate the complicated exposure history of materials in a fusion experiment and measure its effects on the material.

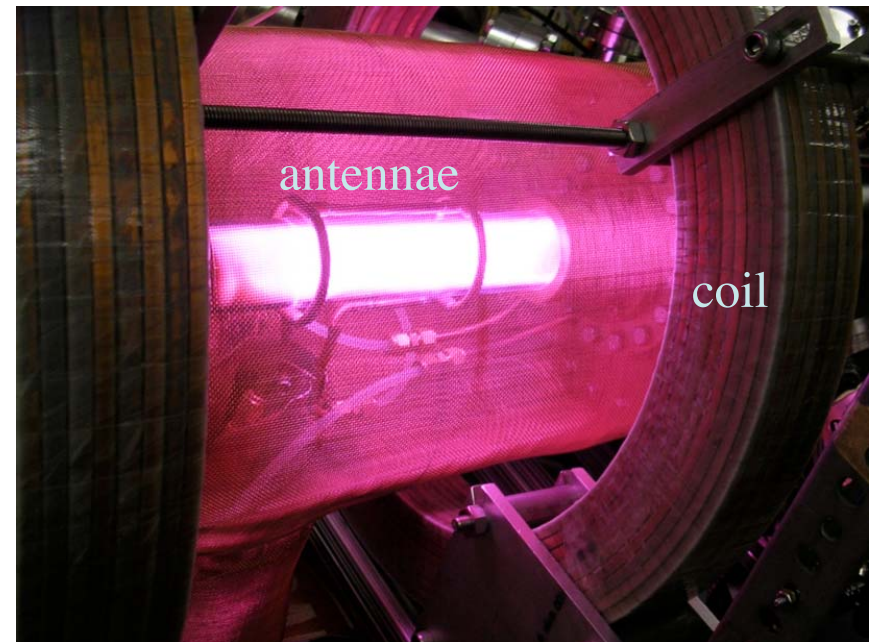
Our 1.7 MV tandem ion accelerator provides non-destructive, depth-resolved diagnosis of material surfaces: e.g. H/D/T retention, erosion, material mixing, isotope tracing



- Range in materials
~ 1-10 microns.
- Low current =
non perturbing.
- Spectra of scattered /
created particles
+
Known slowing down
& cross sections
=
Depth resolution.
- Variety of techniques
with different uses
 - RBS: element i.d.
 - NRA: isotope i.d.
 - ERD: H/D/T/He
 - PIGE: Deep
isotope detection

Helicon source in solenoid B field provides steady-state plasma exposure

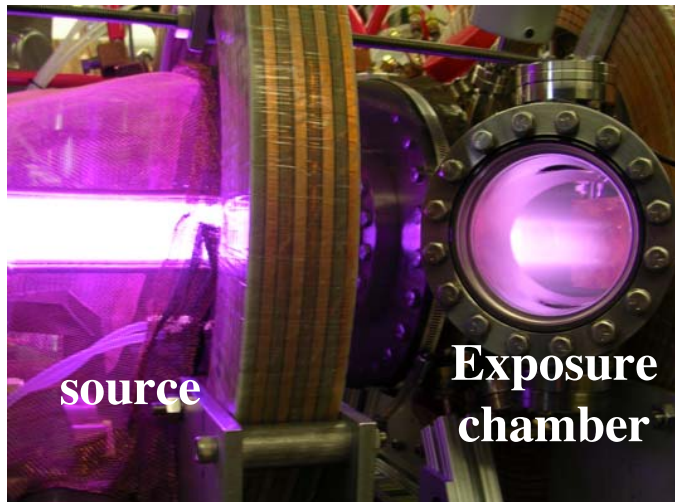
- Cooled RF antennae external to quartz vacuum tube
 - Rapid plasma turn on / off.
 - Minimize vacuum thermal loading.
- Parameters:
 - $P_{\text{RF}, 13.56 \text{ MHz}} = 0.1 - 5 \text{ kW}$
 - $B = 300 - 1000 \text{ G}$
 - Plasma Diameter = 40 mm



Deuterium plasma

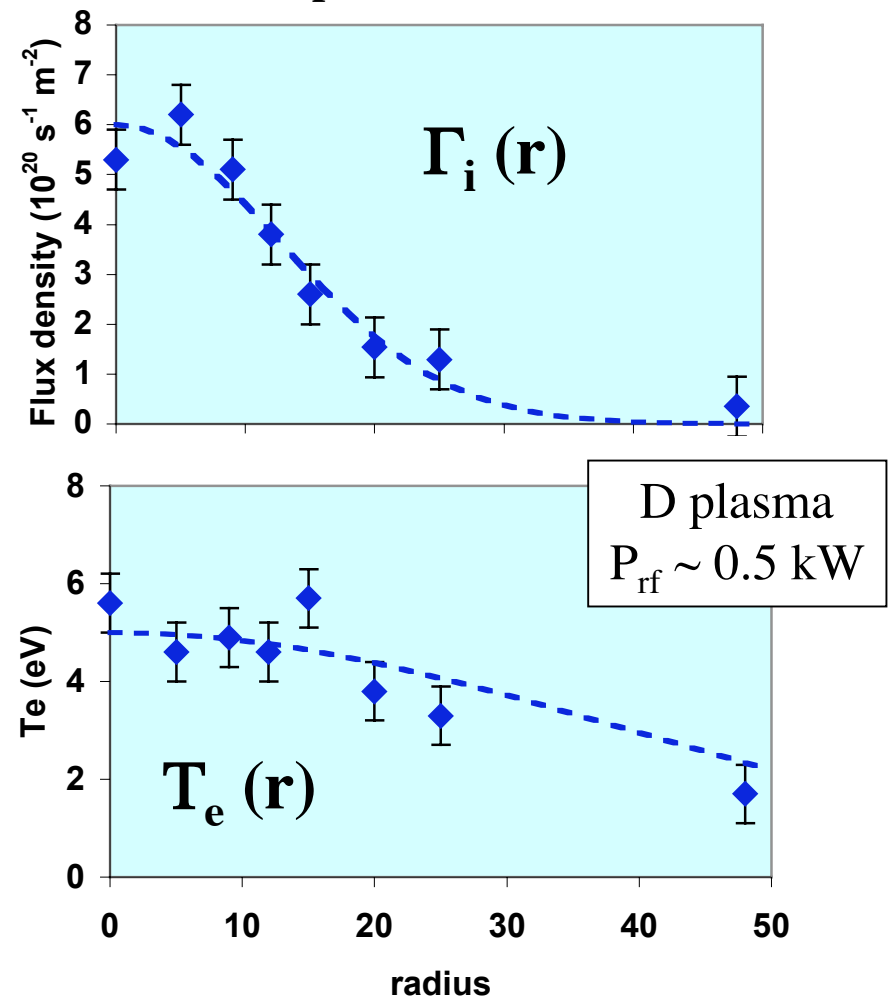
Cylindrical plasma is extracted into an “Exposure chamber” along magnetic field.

Argon plasma



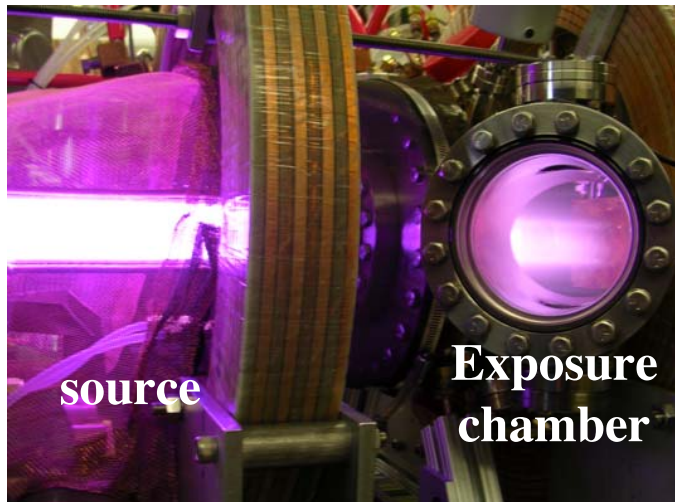
- Profiles:
 - Flux, n_e , : $\lambda_r \sim 18$ mm
 - T_e : $\sim 3-6$ eV

Scanning Langmuir probe
In Exposure Chamber

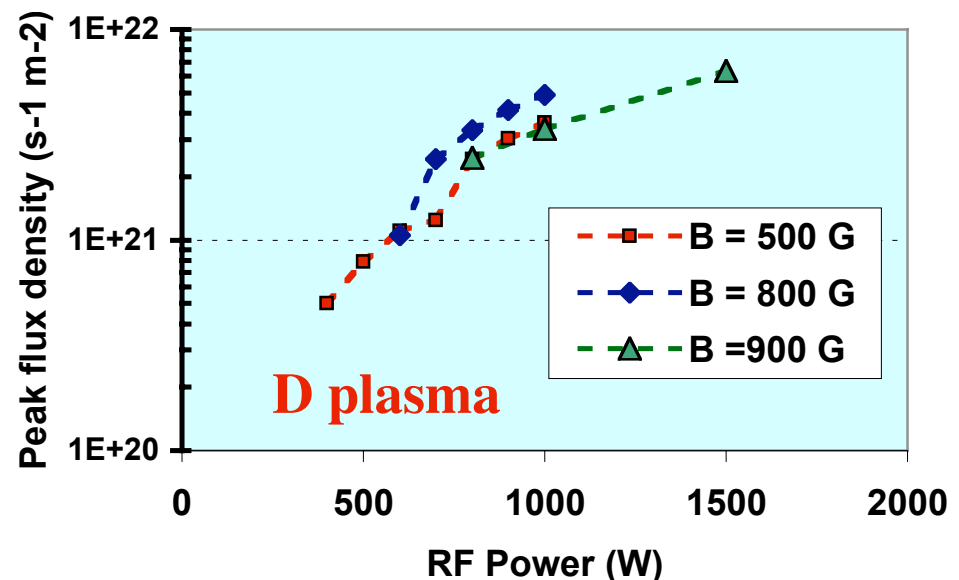
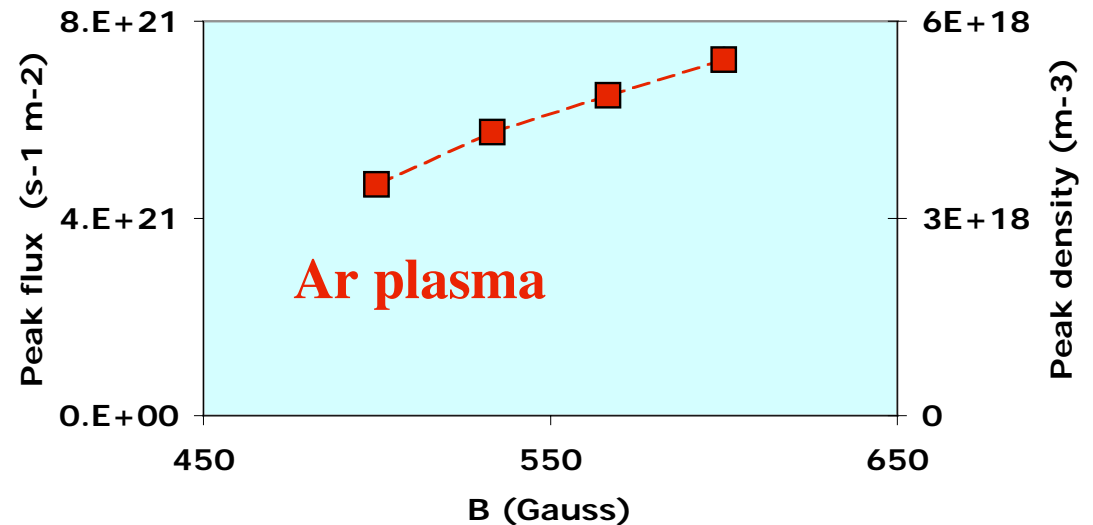


Cylindrical plasma is extracted into an “Exposure chamber” along magnetic field.

Argon plasma



- Profiles:
 - Flux, n_e : $\lambda_r \sim 18$ mm
 - T_e : $\sim 3-6$ eV
- Large range of flux densities available
 $\Gamma_i \sim 10^{19} - 10^{22}$ ions $s^{-1} m^{-2}$



DIONISOS features flexible control of material exposure conditions



- **Copper heat sink with 180 degree rotation.**

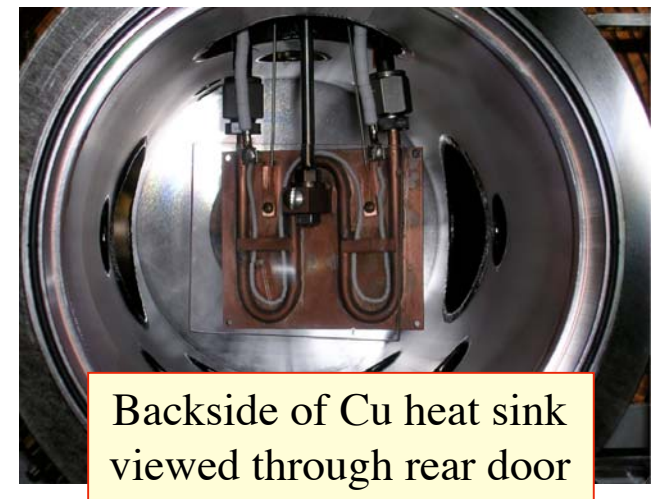
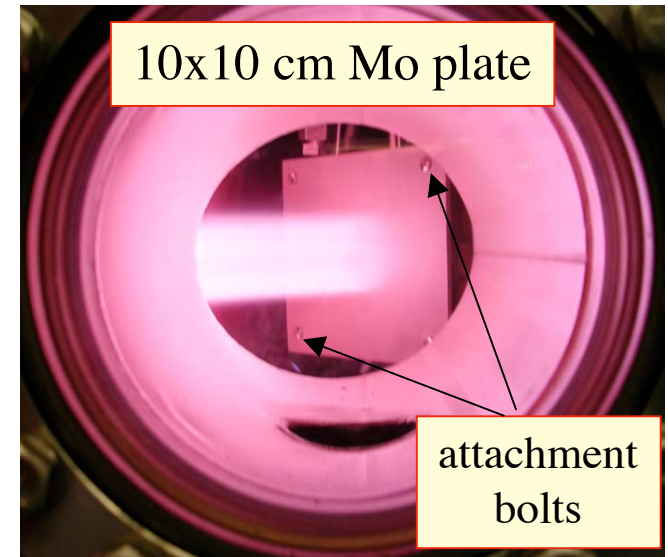
- Accommodates 10x10 cm sample.
- Easy access for sample replacement.
- Flexible beam analysis geometry.

- **Plasma ion bombardment control**

- Biasing up to 500 V, 10 A to set incident ion energy

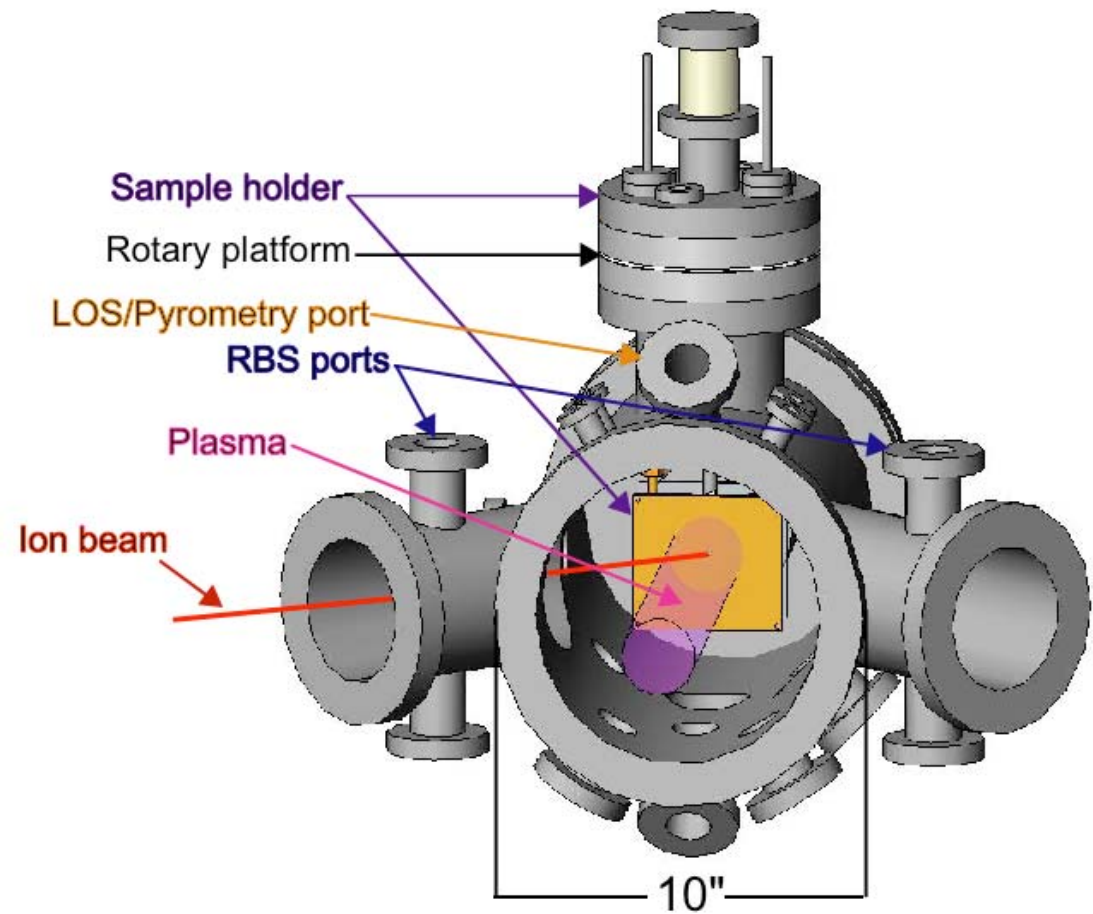
- **Active temperature control**

- Forced water or air cooling.
- Resistive heating for push/pull T control.
- Adaptable mechanical attachments for heat conduction to Cu heat sink.
- Infrared thermography of surface.

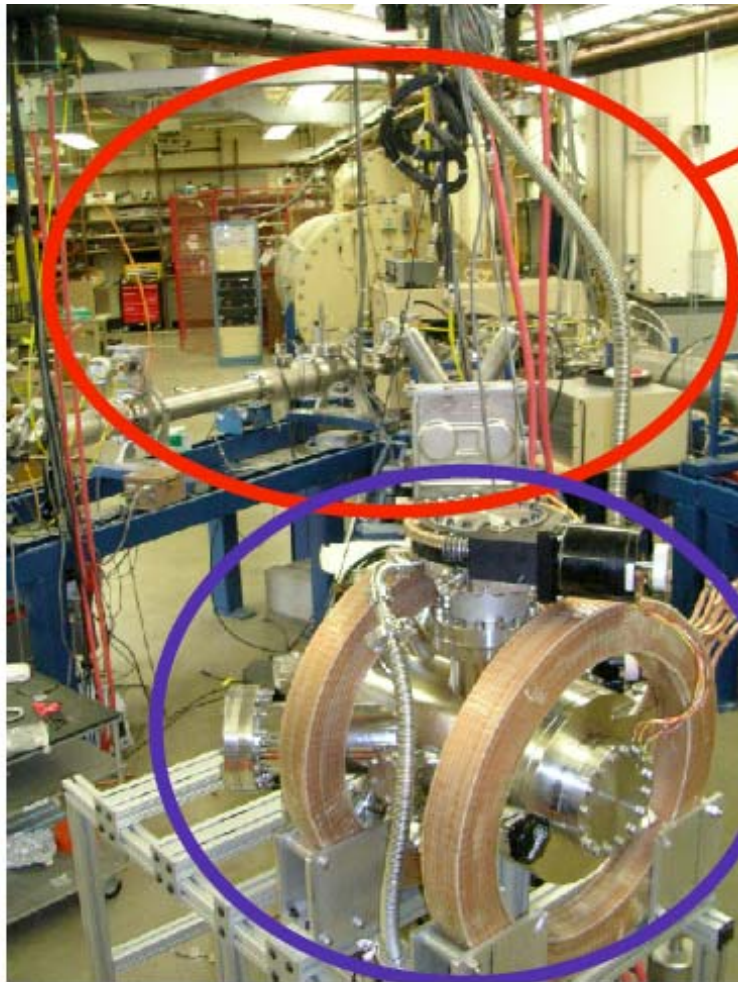


Exposure chamber designed for optimal surface and plasma diagnostic access.

- Exposure chamber:
> 15 ports viewing beam-target or plasma.
- NRA, RBS, ERD & PIGE ion beam analysis available *simultaneously*.
- Large solid-angle gamma detector placed in rear entrant tube



Putting it all together



Ion Accelerator (diagnostic)

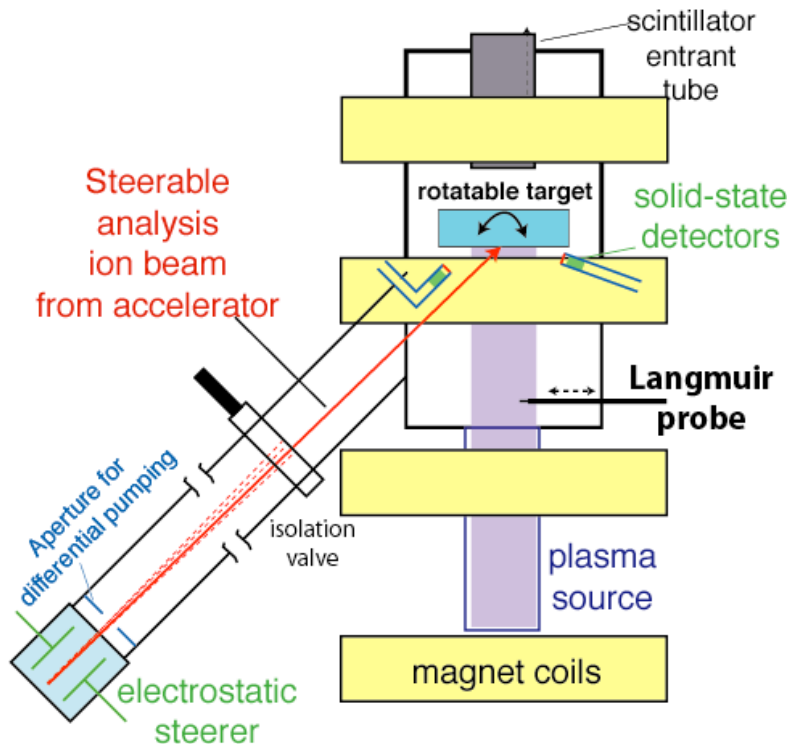


DIONISOS with its support structure and beamline components.

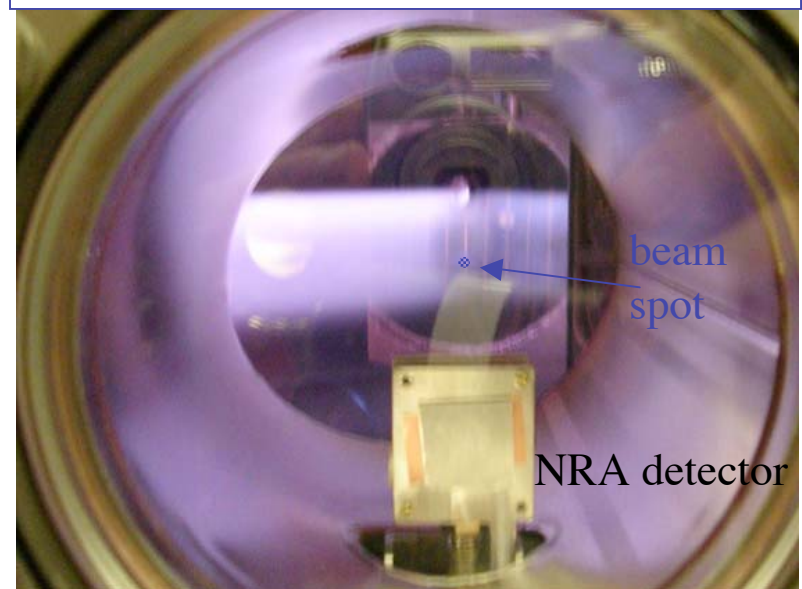
DIONISOS (experiment)

Putting it all together

Beam can be positioned at any location on material sample for surface analysis



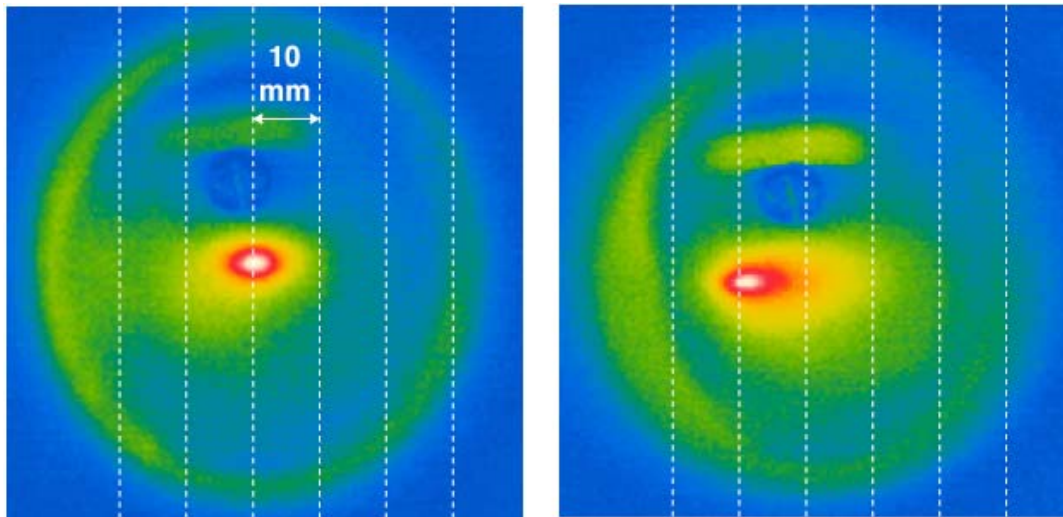
D Plasma & ^3He 3.5 MeV beam
On glass alignment target



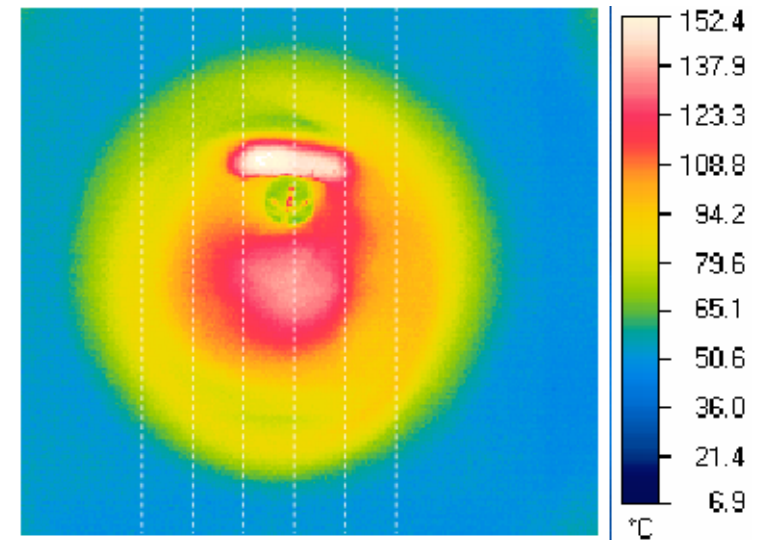
- Upstream X-Y electrostatic steering & quadrupole shaping coils.
- Differential pumping protects upstream accelerator components.
- Beam position control $\sim 2 \text{ mm} \ll$ plasma diameter.

Real-time, in-situ ion beam surface analysis during plasma exposure

IR footprint of beam on glass



IR footprint of plasma on glass



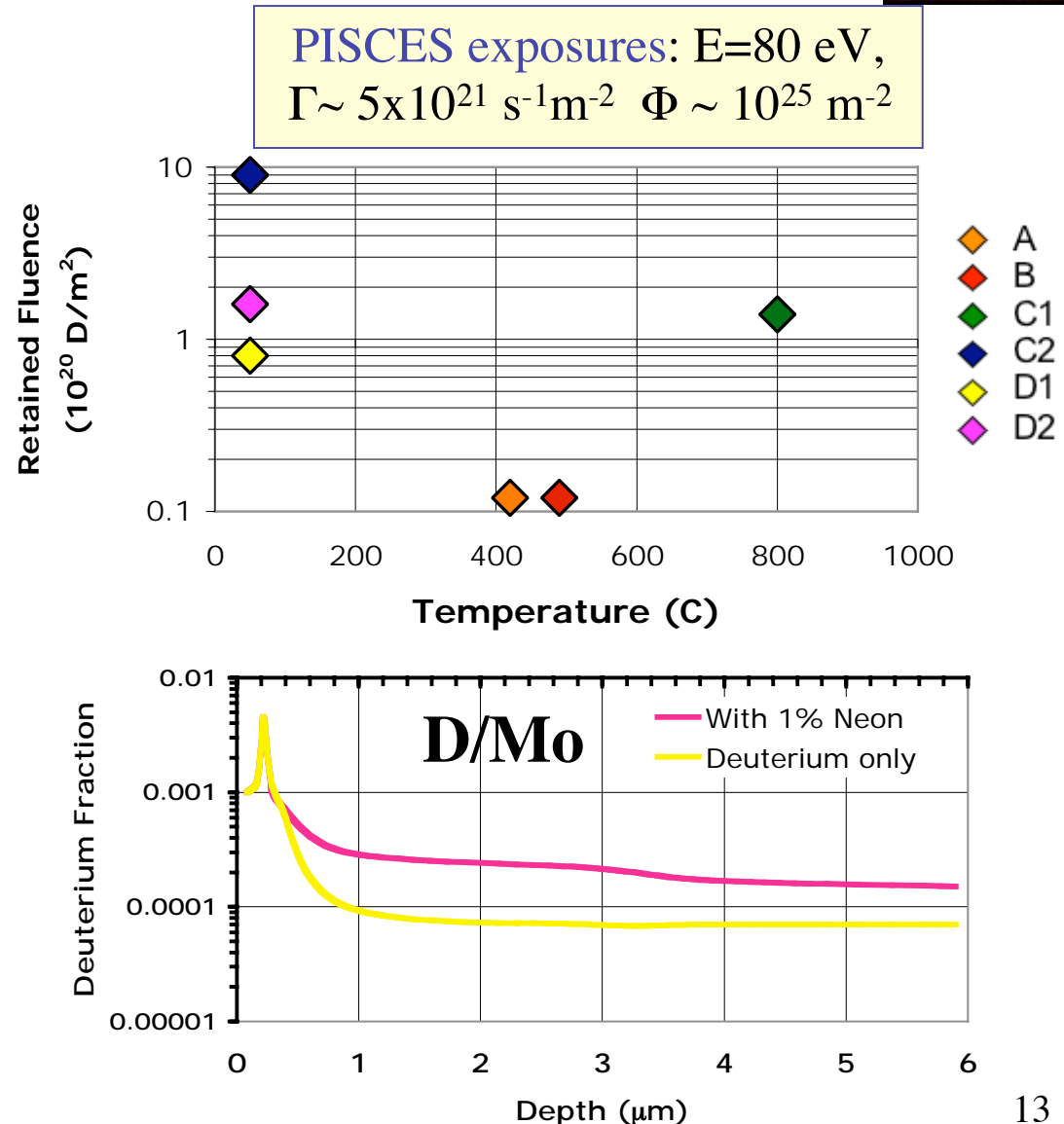
- No significant perturbation to MeV ion trajectories or energy by plasma environment or solenoid magnetic field.

Since Dec. 2005

First physics experiments on DIONISOS: Deuterium retention in Molybdenum



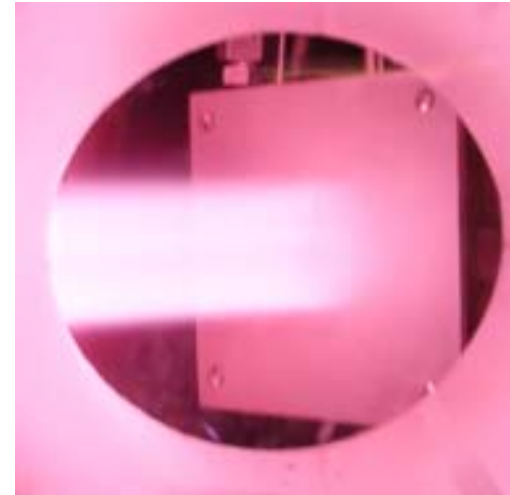
- Motivated by D retention in C-Mod.
- **Initial study in collaboration with UCSD (APS-DPP 05):**
 - D plasma exposure at PISCES.
 - NRA detection of D at Wisconsin
- **Highlights**
 - Strong T dependence but not monotonic?
 - NRA found D trapped at > 5 microns into sample, limit of detection.
 - Apparent dependence of Boron or tile type, but unclear.
 - 1 % Neon seeding enhanced deep D trapping. Effect of vacancy production?



Deuterium plasma exposures of Molybdenum on DIONISOS

- **D plasma**

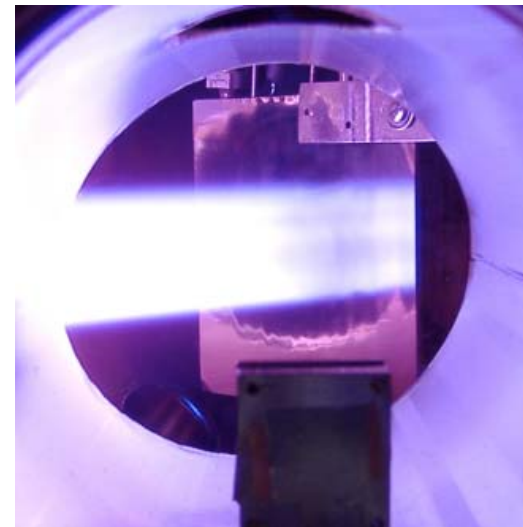
- $P_{\text{rf}} < 1 \text{ kW}$, $B = 500 \text{ G}$.
- Central: $T_e \sim 5 - 6 \text{ eV}$
- $\lambda_{\text{r,plasma}} \sim 18 \text{ mm}$
- Magnetized: $\rho_{\text{D}^+} \sim 5 \text{ mm} \ll \lambda_{\text{i-n}}$
- Peak incident flux density:
 $0.5 - 2 \times 10^{21} \text{ s}^{-1} \text{ m}^{-2}$



Two Mo plates
from C-Mod
1: $T \sim 300\text{-}700 \text{ K}$
2: $T \sim 300 \text{ K}$

- **Exposure conditions**

- $V_{\text{bias}} \sim E_{\text{ion}} = 100 \text{ V}$
 - **No vacancy production.**
 - **No sputtering.**
- Mo plates cleaned, but not annealed before exposure.



High purity
Mo foil:
 $T \sim 400 \text{ K}$

^3He Nuclear Reaction Analysis (NRA)

Deuterium density profiles in Mo

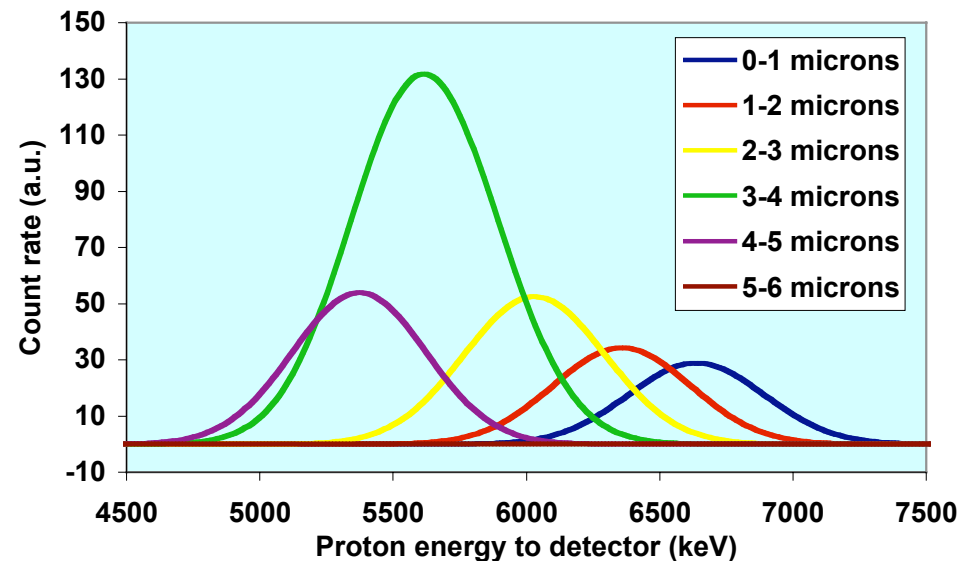
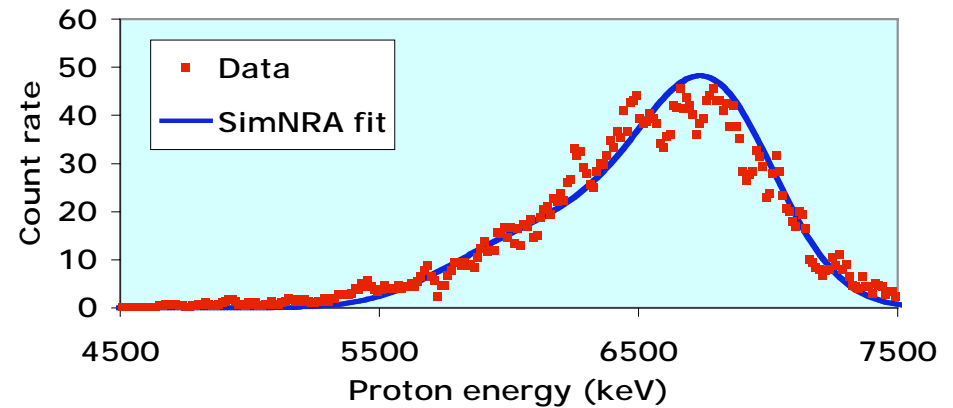


- Parameters:

- $E_{^3\text{He}} = 0.5 - 4.5 \text{ MeV}$
- $I_{^3\text{He}} \sim 1 - 2 \text{ } \mu\text{A}$
- Depth resolution: $\sim 0.5 \text{ } \mu\text{m}$
- Range $\sim 3 - 5 \text{ } \mu\text{m}$
- Sensitivity: $\text{D/Mo} > 10 \text{ appm}$

- Surface impurity checks

- NRA: Carbon, Boron
- ERD: surface H / D



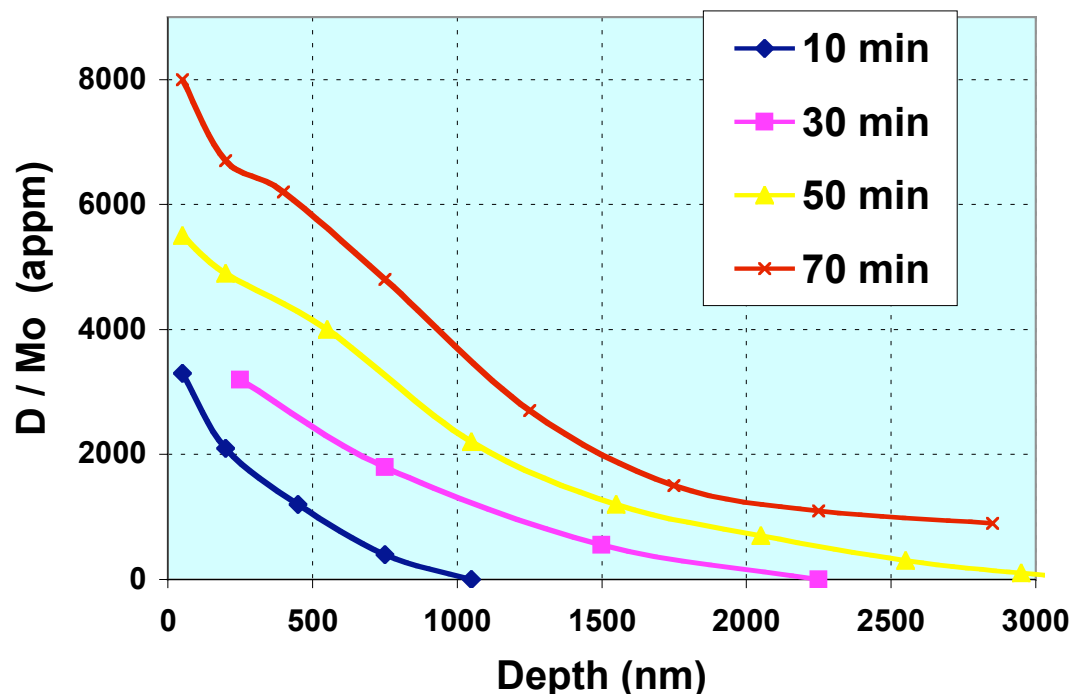
SIMNRA (M. Mayer et al.)

Simulation of
1% D/Mo layers of
1 micron depth
At various depths

25 micron Mo foil at 370 K: Deuterium becomes trapped progressively deeper into Mo with plasma exposure



NRA D profiles with increasing
D plasma exposure

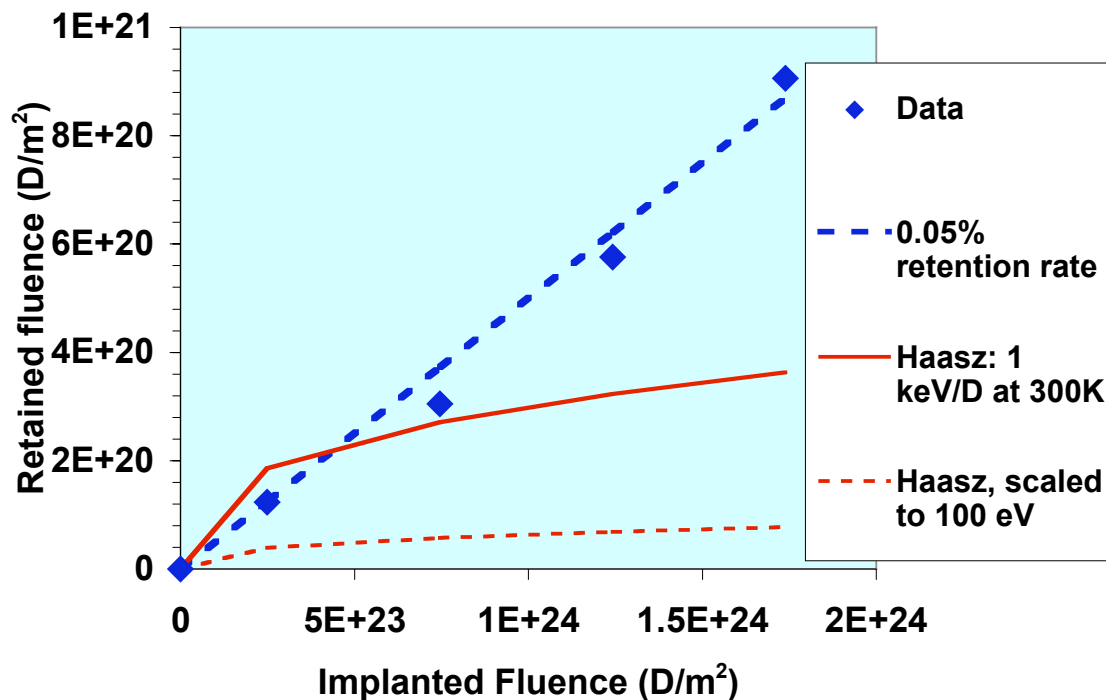


- NRA data taken *after* each plasma exposure.
- Natural trap concentration ~ 50 appm.
- Not diffusion limited: depth scale ~ 20 microns in 1000s at 370 K,
 - So appears that trapping is evolving
- Trap mechanism?
 - No vacancies produced.
 - Bubbles?

Mo foil at 370 K:

Retention increases linearly with fluence

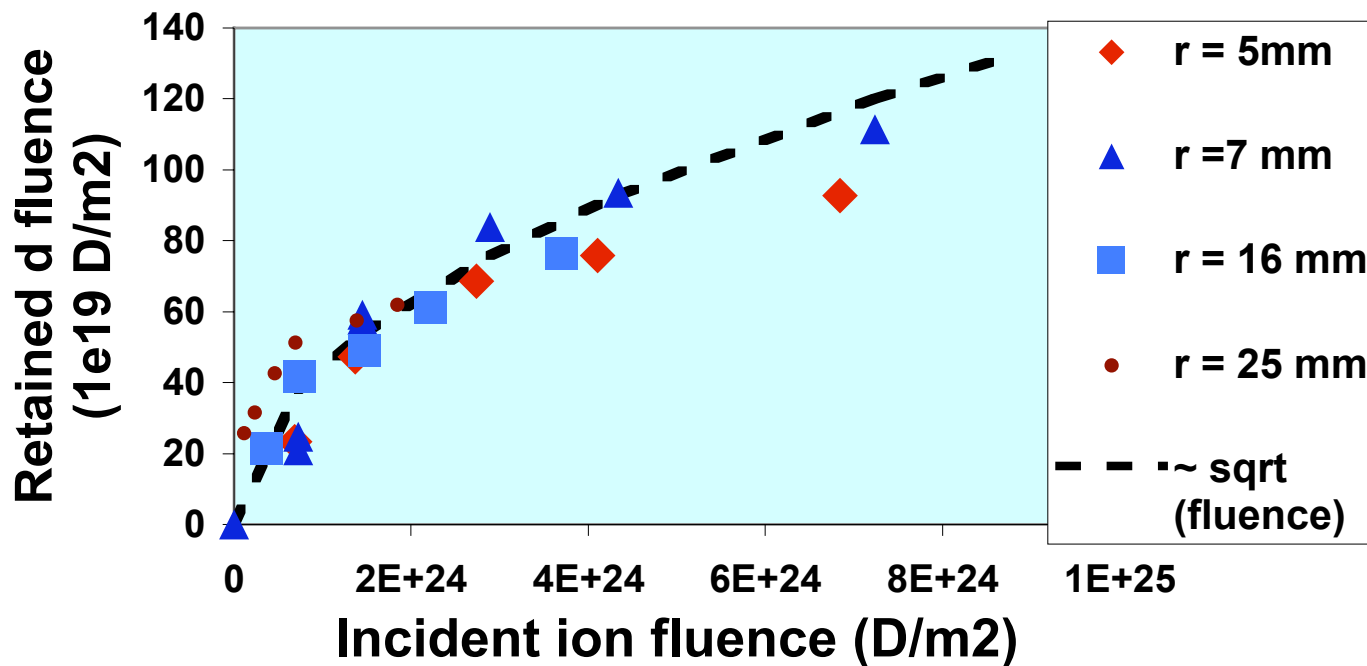
Retention rate $\sim 0.05\%$ per D ion



- Linear increase in retained D with fluence like C-Mod
- But retention rate ~ 10 lower than inferred from C-Mod.
- Accurate D accounting becomes difficult since D surpassing NRA depth limit ~ 3 microns.

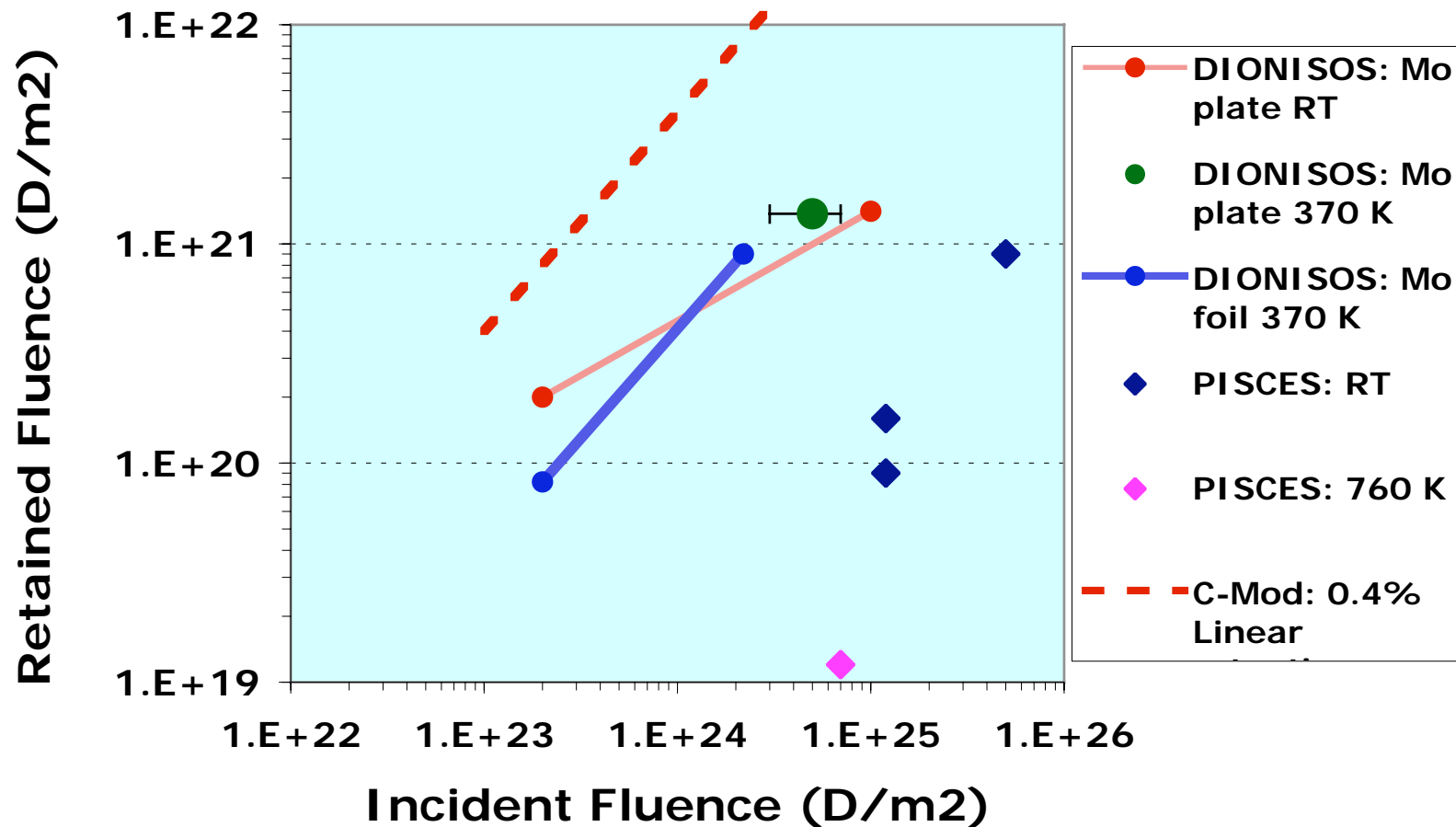
Mo plate at RT:

Retention increases as square root of fluence
Suggesting diffusion limited trap process



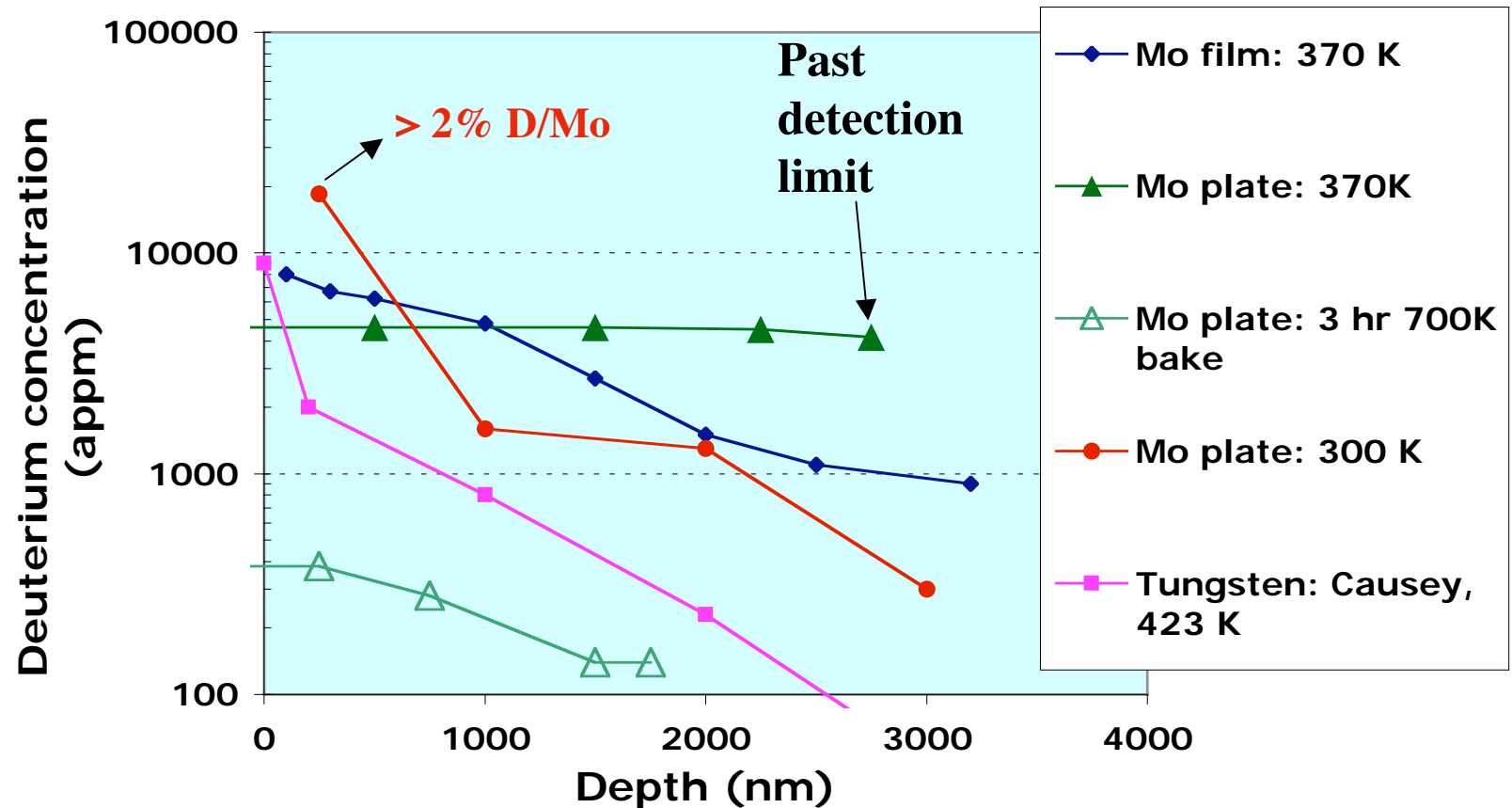
Overall retention rates approach those found on C-Mod, but remain systematically lower

Effects of flux, boron & temperature to be investigated



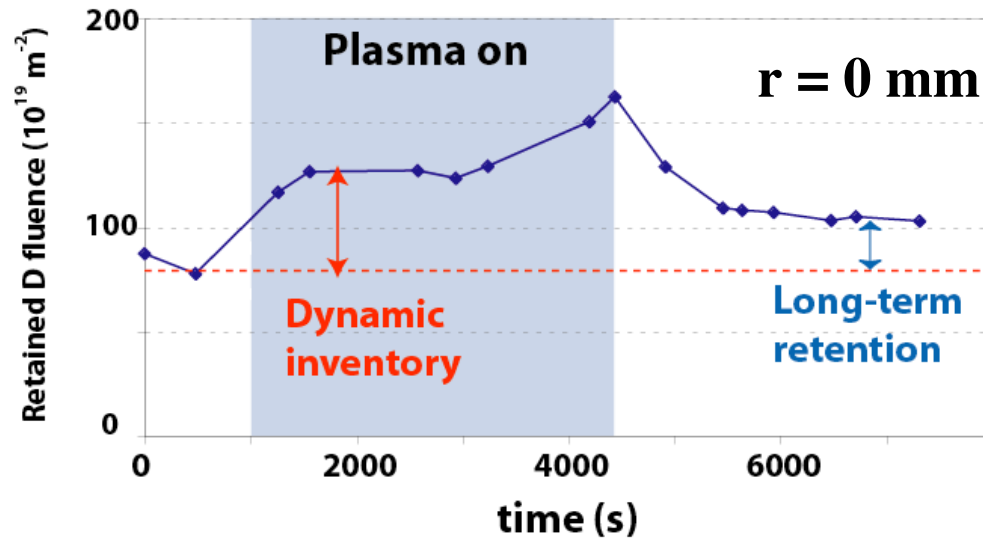
D depth retention profiles vary widely with exposure conditions & material.

Indications of deep trapping in many cases

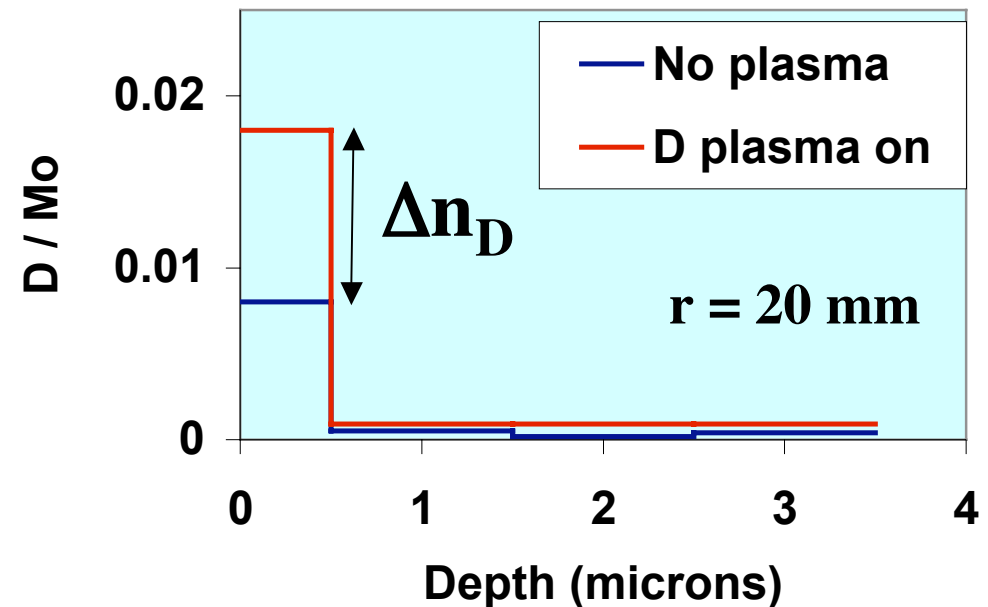
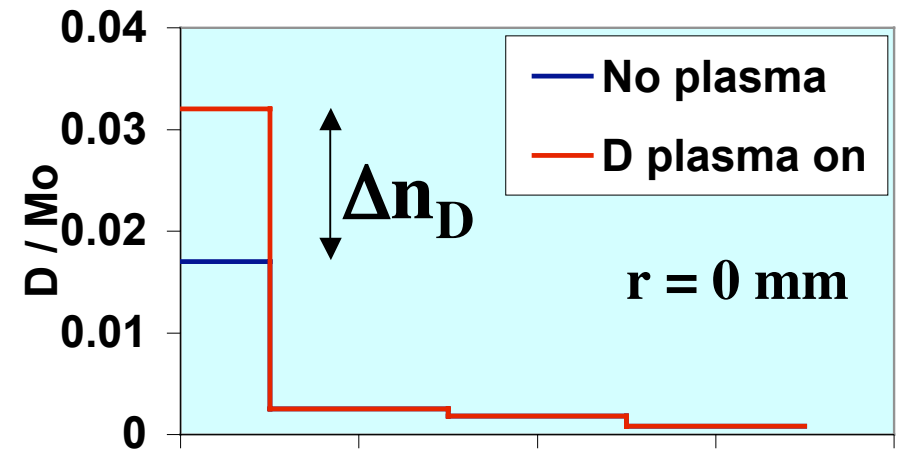
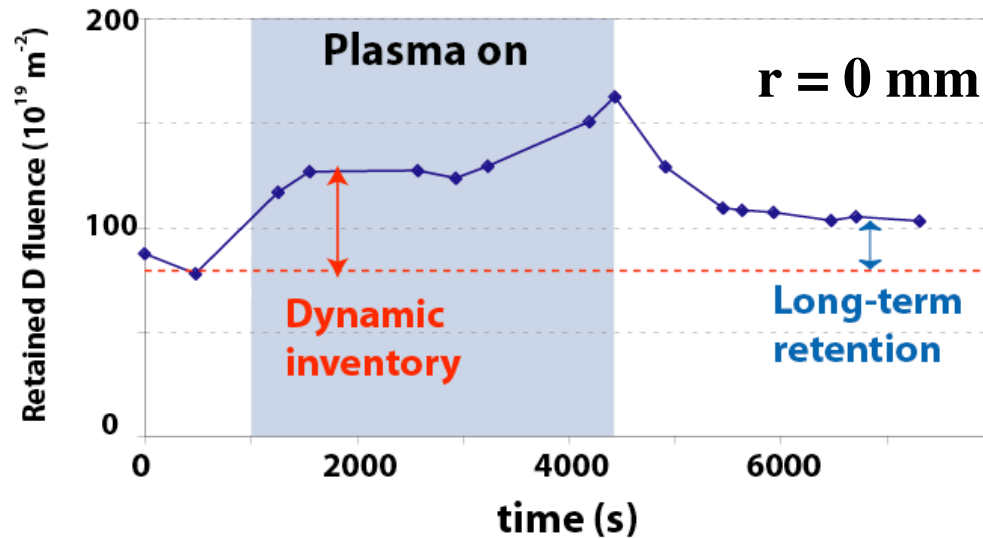


Incident Fluences $\sim 10^{24} - 10^{25} \text{ D/m}^2$

Mo plate at RT with plasma on: Dynamic inventory of deuterium is ~ doubled during plasma exposure



Mo plate at RT with plasma on: NRA depth profiles show the dynamic deuterium concentrated near surface

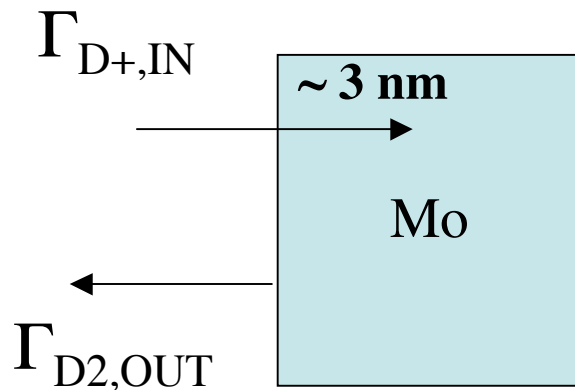


Mo plate at RT with plasma on:

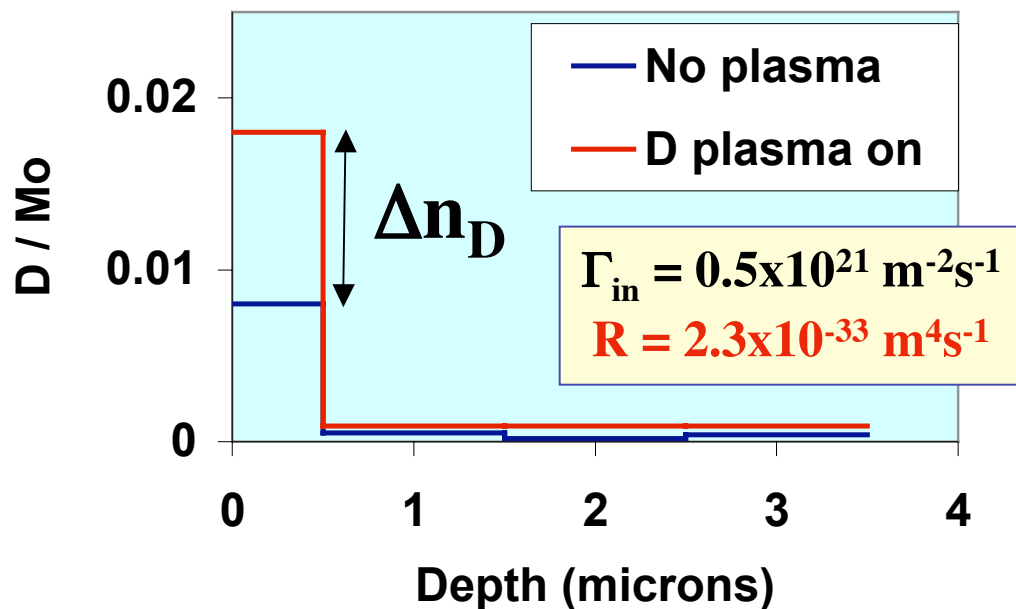
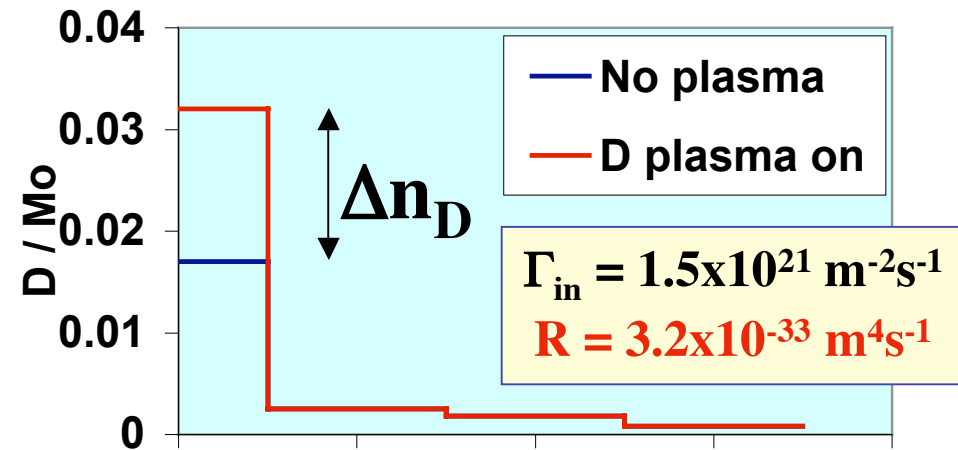
Dynamic inventory of deuterium accurately measures D surface recombination rate.



- Dynamic D inventory builds up due to finite rate for surface recombination rate --> **Coefficient: $R(T)$ m^4/s**



$$\Gamma_{D+,IN} = \frac{1}{2} \Gamma_{D2,OUT} = \frac{1}{2} (\Delta n_D)^2 R$$

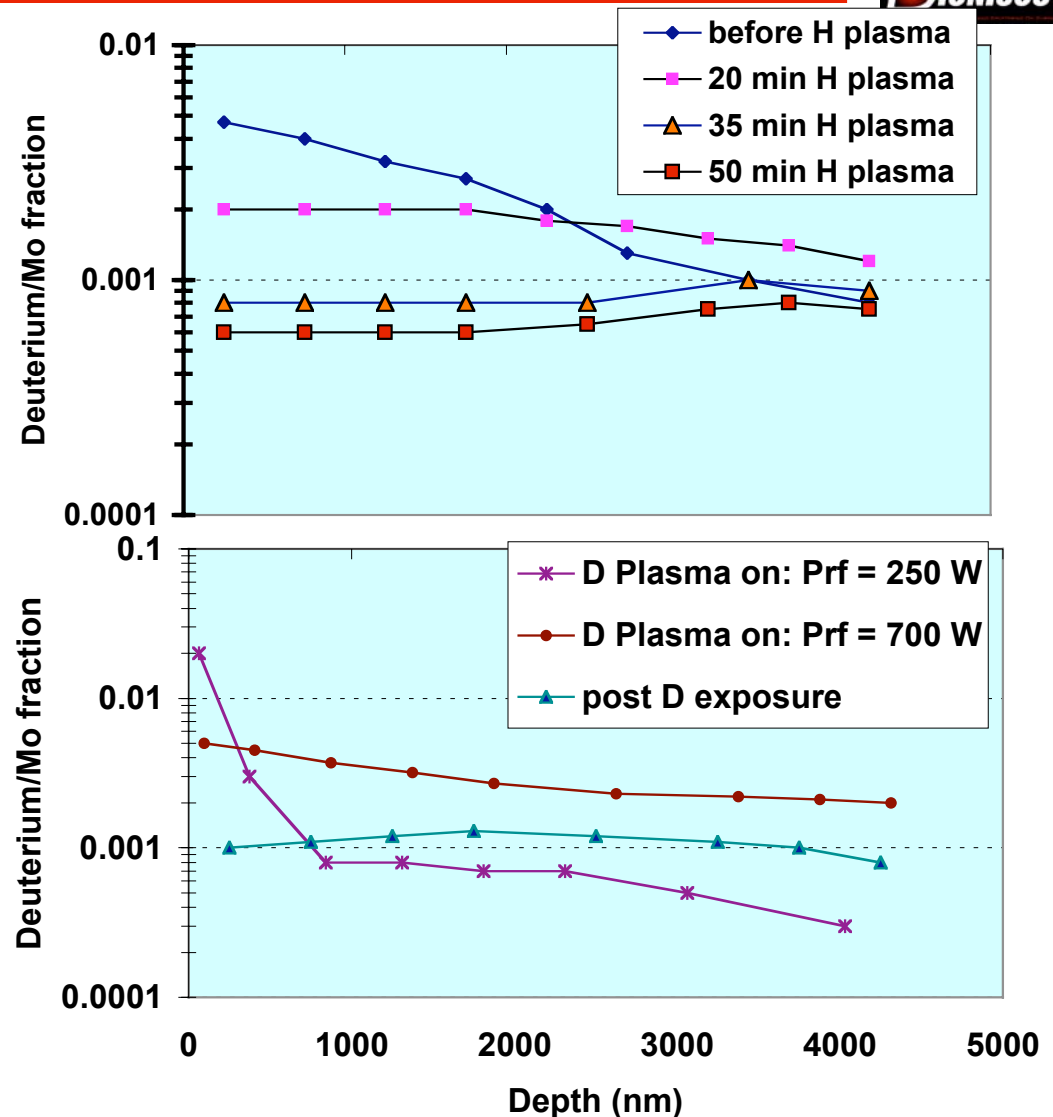


More dynamics:

Isotope effects from H bombardment & D retention during re-exposure to D



- H plasma exposure results in depletion of D retained from previous D plasma exposure.
- **Dynamic measurements:**
 - $\Delta n_D \rightarrow R = 5 \times 10^{-32} \text{ m}^4 \text{ s}^{-1}$ at 370K
 - Re-exposure to D plasma filled back D, first near surface then deep to detection limit.
 - Relevant to isotopic plasma recovery of Tritium



What DIONISOS brings to PFC research

We look forward to collaborations with the PFC community



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 - 2) In-situ ion beam surface analysis WITHOUT removal of the sample
but that is only the overall description
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